Provision of Grid Services by PV Plants with Integrated Battery Energy Storage System

Preprint

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***Abstract*—Battery energy storage systems (BESS)—because of their tremendous range of uses and configurations—may assist photovoltaic (PV) integration in many ways by increasing power system flexibility. In this paper, we describe results of a research project conducted by the National Renewable Energy Laboratory (NREL) and First Solar to develop controls and demonstrate many use cases for PV-BESS systems, including (1) matching generation to load through time shifting, by reducing PV curtailment; (2) promoting higher levels of PV penetration by balancing the grid through ancillary services; (3) using PV-BESS systems to provide wide-area stability services in the form of oscillation damping controls; and (4) using gird-forming BESS to enable black-start and islanded applications for PV-BESS systems.**

In the paper, we also describe the unique multi-MW test and validation platform developed at NREL for conducting research on fielded utility-scale PV-BESS systems. The platform consists of First Solar's 0.43-MW PV power plant and NREL's 1-MW/1-MW BESS, 2-MW PV power supplies, and 7-MVA power electronic grid simulator interfaced with industrial plant controllers and power-hardware-in-the-loop capability.

Keywords—PV, BESS, grid services, hybrid systems

I. Introduction

Although utility-scale solar photovoltaic (PV) power plants are becoming a cost-effective energy resource [1], there is belief within industry that the increasing penetrations of PV technologies could potentially impact grid reliability [2], [3]. This is a result of the variability across timescales and forecast uncertainty of the solar energy resource and the impacts on both distribution and transmission systems. This can cause utilities to severely limit PV installations or assign higher PV integration costs when considering a least-cost portfolio of resources [4]. With PV's increased proportion of energy to the generation mix, advanced PV controls and grid integration features can minimize grid impacts from variability and, in many cases, can improve reliability, stability, and power quality [5]. Deployment of utility-scale, grid-friendly PV power plants that incorporate advanced capabilities to support grid stability and reliability is essential for the large-scale integration of PV generation into the electric power grid.

A typical modern utility-scale PV power plant is a complex system of large PV arrays and multiple power electronic inverters, and it can contribute to mitigating the impacts on grid stability and reliability through sophisticated, automatic "grid-friendly" controls [7]. Integration with energy storage could assist PV integration in many of ways by increasing power system flexibility. The cost of battery-based energy storage has declined dramatically in recent years [8], presenting an opportunity for energy storage not only to perform functions currently met by conventional generators that serve peak electricity demand but also to provide new opportunities for economic hybridization with variable generation, including solar PV. The use of storage can change and customize the "shape" of PV production to better match load and peak demand in many power systems, make PV generation more flexible, and facilitate very high levels of PV solar generation without curtailment [9], [10].

The degree to which the PV and storage are coupled (both physically and operationally) can be divided into four distinct categories:

- Independent—PV and battery are not colocated and do not have a point of common coupling (PCC); energy stored in battery could come from either PV or grid
- AC-coupled—PV and battery are colocated and have a common PCC at the plant substation; energy stored in battery could come from either grid or PV
- DC-coupled—battery is connected to DC side of PV inverters; energy stored in battery could come from either grid or PV
- Tightly DC-coupled—battery is connected to DC side of PV inverters; energy stored in battery could come only from PV.

Each PV storage configuration has advantages and disadvantages [9]–[12]. In this work, we focus on developing controls and conducting demonstration testing for AC-coupled PV-BESS systems in which the PV and battery energy storage systems (BESS) are colocated and share a PCC. PV-BESS systems do not share any physical components (such as inverters, transformers, and protection), but they have a common controller that can operate both PV and BESS either as a single plant or two independent systems. The general configuration of a utility-scale PV-BESS plant used to develop and demonstrate many control concepts during this project is shown in Figure 1. As colocated resources, solar PV generation and BESS naturally share the same infrastructure (substation, point of interconnection, tie-lines) and a plant-level controller that operates both technologies as one utility-scale asset interacting with a single market interface.

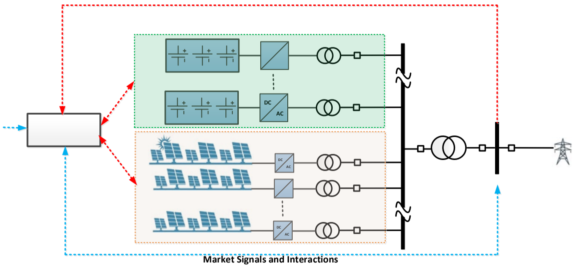

Figure 1. AC-coupled PV-BESS plant configuration

This research project conducted by the National Renewable Energy Laboratory (NREL) and First Solar leveraged and benefited from the knowledge and field experience accumulated from previous work [5], [13] with First Solar and other partners (CAISO, ERCOT, AES, PREPA, etc.) and advanced prior work by:

- Combining PV plant and BESS controls to provide the existing and future projected ancillary service products by various balancing authorities and system operators in U.S. interconnections and island systems
- Developing controls with increased complexity because of the multi-technology nature of PV-BESS operation
- Demonstrating controls by the utility-scale PV plant combined with BESS that can qualify for participating in the existing ancillary service spinning and nonspinning reserve markets
- Demonstrating new PV-BESS controls that can be required from variable generation by evolving ancillary service markets, such as primary frequency response (PFR), fast frequency response (FFR), down ramp control, short-term variability smoothing, and voltage control
- Developing new advanced ancillary service controls by PV-BESS plants for inter-area oscillation damping, subsynchronous resonance mitigation, mitigation of control interactions, etc.
- Demonstrating grid-forming controls by BESS to provide resiliency services (black start, islanded operation, system restoration) to hybrid PV-BESS plant.

II. TEST PLATFORM

A. PV Plant

A 430-kW PV array was installed at NREL's Flatirons Campus. The plant uses fixed-tilt PV modules with 25-degree tilt angle facing south, combined in 14 parallel rows, as shown in the aerial photo of the complete plant (Figure 2). The array was divided into six subarrays, each connected to individual string inverters. The PV plant has a central power plant controller (PPC) implemented in the SEL real-time automation controller (RTAC) platform.

B. BESS

The BESS used in this project is rated for 1 MW/1 MWh, and it uses a 1-MW Lithium-ion battery pack connected to SMA's 2.2-MVA Storage Central inverter (Figure 3). The BESS inverter can operate in both grid-following and grid-forming modes.

Figure 2. First Solar's 430-kW PV plant installed at NREL's Flatirons Campus

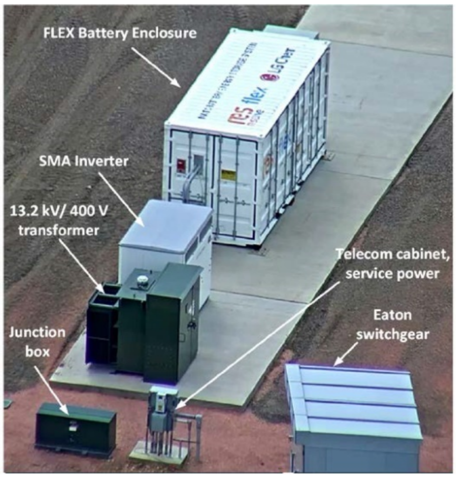

Figure 3. 1-MW/1-MWh BESS

C. Test and Validation Platform

A test platform was developed by combining the PV array and BESS, both interconnected with the 13.2-kV test bus at NREL's Flatirons Campus. This system has the flexibility to be configured so that both the PV plant and BESS can operate in a regular grid-connected mode or be switched to operate under controlled grid conditions interconnected with a 7-MVA grid simulator, as shown in Figure 20. (This figure is at the end of paper to ensure clarity of the image.) The grid simulator—or controllable grid interface (CGI)—operates at 13.2 kV. The CGI is combined with a real-time digital simulator as a power-hardware-in-the-loop (PHIL) platform, so closed-loop experiments for the PV-BESS connected to emulated models of power systems of different sizes can be conducted. A detailed description of the CGI and characteristics of the PHIL platform were described in detail in [14].

III. PLANT CONTROLLER

The NREL team developed and implemented a BESS controller based on the standard SEL RTAC industrial controller platform (the same platform as the PV PPC). The

BESS RTAC controller is communicating with the First Solar PPC controller, which was developed on the same hardware platform. This makes the integration of the NREL-developed controller with the existing First Solar PPC an easy process. The user interface for the BESS supervisory control and data acquisition system allows remote start and stop of the BESS system and activation of desired control modes, including the ability to switch between grid-following and grid-forming modes.

The BESS controller was designed to provide various forms of active and reactive power control. It has the capability to provide inertial response, FFR, and PFR by the PV-BESS plant. In addition, the BESS can provide reactive power control in the form of kVAR-voltage droop during dynamic and fault conditions. The implemented control diagram for all these control functions was developed by NREL and is shown in Figure 21 (at the end of the paper for better clarity).

All BESS active power controls components can be combined in a single simplified equation, so at any instant in time, the total BESS power (injecting or absorbing) is:

$$P_{bess}(t) = P_o(t) + \Delta P_{soc}(t) + \Delta P_i(t) + \Delta P_{FFR}(t) + \\ + \Delta P_{droop}(t) + \Delta P_{AGC}(t) \qquad (1)$$

where $P_o(t)$ is the BESS dispatch set point; $\Delta P_{soc}(t)$ is the portion of the commanded power set point for the BESS state of charge (SOC) control; $\Delta P_i(t)$ is the BESS inertial response (or response proportional to the rate of change of frequency); $\Delta P_{FFR}(t)$ is BESS FFR response; $\Delta P_{droop}(t)$ is the BESS droop response; and $\Delta P_{AGC}(t)$ is the BESS automatic generation control (AGC) response.

Depending on the type of service that the BESS is providing, the individual components in (1) can be activated at the proper times. For example, $\Delta P_i(t)$ will start first, at the beginning of the event, as soon as a large rate of change of frequency is detected; then either $\Delta P_{FFR}(t)$ or $\Delta P_{droop}(t)$ will kick in (the BESS can provide either FFR or droop response, but it cannot do both at the same time). The $\Delta P_{AGC}(t)$ component will follow the AGC set points from the system operator for secondary frequency control and frequency regulation. Equation (1) can be expanded to show components of interest in more detail:

$$P_{bess}(t) = P_o(t) + \Delta P_{soc}(t) - 2H\frac{df(t)}{dt} + \Delta P_{FFR}(t) - \\ \frac{f_o - f(t)}{droop} + \Delta P_{AGC}(t) \qquad (2)$$

where f_o- is the scheduled grid frequency, and $f(t)$ is the grid frequency at any point in time.

Similar controls were developed and implemented for the PV plant as well. The PV-BESS plant can provide grid services by the BESS component only; by the PV component only; or collectively by both the PV and BESS, depending on the operational status of the plant, SOC, etc. For example, the theoretical frequency droop response capability of the PV and BESS is shown in Figure 4 in per unit. In this case, the droop response by the BESS component of a PV-BESS plant is drawn for a case when the BESS happened to be at zero power, so it has equal headroom to inject or absorb power, depending on the nature of the transient event (underfrequency or overfrequency). For a PV plant to provide a droop response, it needs to be curtailed to have enough headroom to increase its production to the level determined by the droop settings during the underfrequency events. For overfrequency events, a PV plant can provide an aggressive droop response. It is anticipated that the prevailing role of the PFR provision of PV-BESS plants will be based on the BESS components providing such services instead of curtailing the PV components of PV-BESS plants.

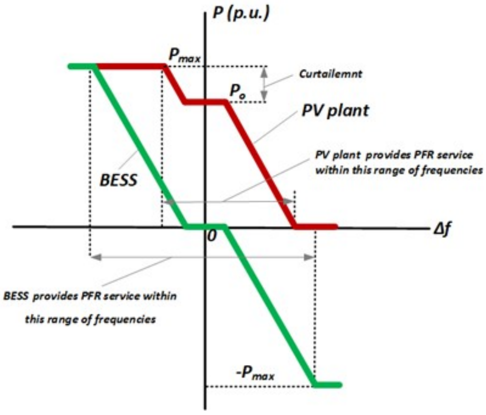

Figure 4. Frequency droop response by PV-BESS system

The overall combined reactive power capability measured for the 430-kW PV plant and the 1-MW/1-MWh BESS is shown in Figure 5. As expected, the aggregate reactive power capability of this hybrid PV-BESS plant is larger than the reactive power capability of individual components. This ideal shape assumes a low-impedance connection and that the steady grid voltage could change depending on the characteristics of each point of interconnection.

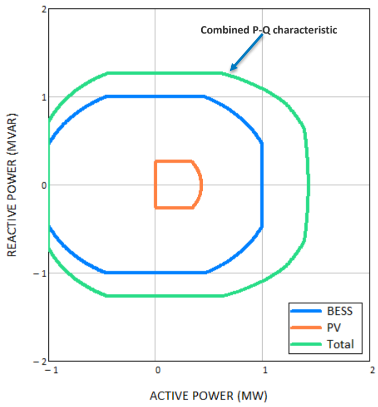

Figure 5. Measured P-Q capability of PV-BESS system

IV. Response Times of PV-BESS System

The response time of the 430-kW PV plant for the active and reactive power set points was measured in grid-connected mode during the peak PV production hour. The plant controller was set to receive rectangular active and reactive power set points simultaneously, as shown in Figure 6. Before starting this test, the plant was curtailed to test the active power response in both up and down directions. The plant was receiving rectangular active and reactive power set points at different frequencies (0.1 Hz and 0.05 Hz, respectively). Several important observations from Figure 6 are:

- The PV plant, which consists of string inverters from different vendors, can follow both active and reactive power set points with a high level of precision.
- The plant can follow reactive power set points in both kVAR injection and absorption modes.
- A delay of approximately 300–400 ms was observed until both active and reactive power reached the set point because of a combination of communications delays and internal ramp limits in the inverters.
- Active and reactive power can be controlled independently of each other and can follow the set points with a high level of precision if the current limits of the inverters are not exceeded.

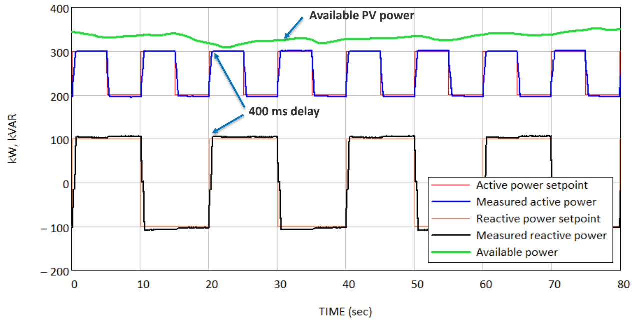

Figure 6. Measured PV plant response

Several tests for BESS were conducted as well to measure the ability of the battery system to follow the active and reactive power set points. The BESS response was tested in both grid-following and grid-forming modes of operation.

One example of the BESS following rectangular active power set points in grid-following mode is shown in Figure 7. A response delay of approximately 100 ms was introduced mainly by communications.

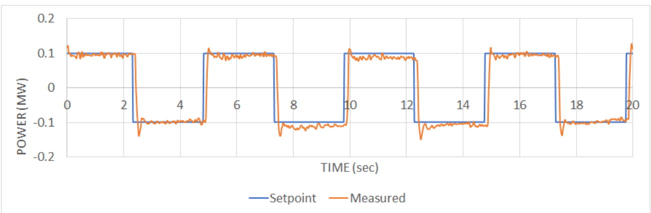

Figure 7. BESS response to active power set points in grid-forming mode

In these tests, both the active and reactive power of the PV plant and BESS were measured on the 13.2-kV sides of the transformers.

FFR is another method to use PV-BESS systems to compensate for a sudden loss of generation or load. This can become a very efficient frequency response tool for system operators, but it requires precise knowledge of loss of magnitude so participating plants can be commanded to change their power outputs accordingly. The examples of active power response tests shown in Figure 6 and Figure 7 demonstrate that PV-BESS systems can provide FFR if the plant controller receives the active power set point from the power system operator.

V. PFR by PV-BESS System

Several experiments were conducted on the 430-kW PV plant to demonstrate its ability to provide droop response when exposed to real frequency events emulated by the CGI. The PV plant demonstrated good PFR for both the 5% and 3% droop settings, as shown in Figure 8 for the 3% droop case.

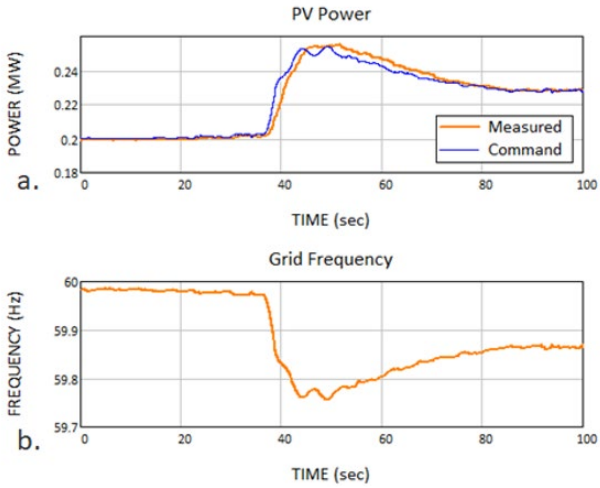

Figure 8. PV plant providing 3% droop response

The measured ability of the BESS to provide droop response is shown in Figure 9.

It is anticipated that the prevailing role of the PFR provision of PV-BESS plants will be based on the BESS component providing such a service instead of curtailing the PV component of PV-BESS plants; however, in some cases, when PV curtailment is present, both the PV plant and BESS can participate in PFR.

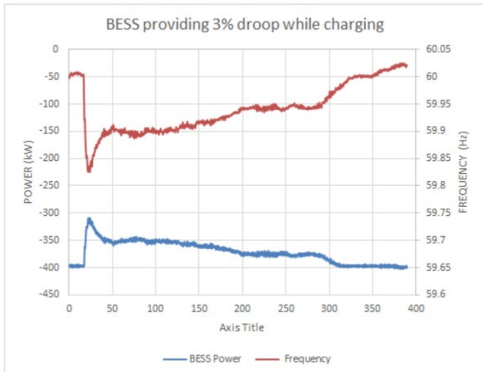

Figure 9. BESS providing 3% frequency droop response in grid-following mode

VI. PV-BESS System Participation in AGC

In this section, we show example results of a 430-kW PV plant operation when following the set points generated by the NREL controller. These set points were calculated from the historic 4-s area control error (ACE) time series recorded by one U.S. balancing authority. The historic ACE data were scaled down by the NREL controller to a level corresponding to the rating of the 430-kW PV plant. The results of testing for the 430-kW PV plant participating in AGC are shown in

Figure 10 and Figure 11 for variable and clear-sky conditions, respectively.

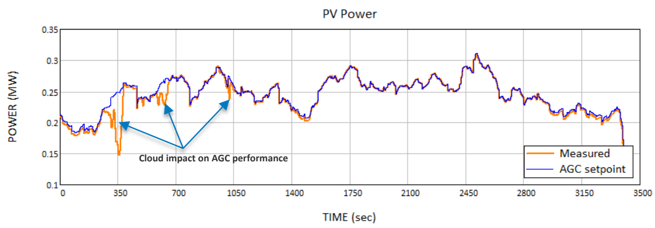

Figure 10. PV plant following AGC set point under cloud variability conditions

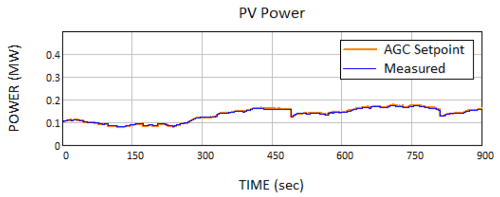

Figure 11. PV plant following AGC set point under clear-sky conditions

These figures show that the curtailed plant (10% below available peak power) is fully capable of following the AGC signal with high precision when there is enough headroom between the plant's operational point and peak available power. During fast cloud movements, however, the plant output can decline rapidly. To avoid these situations, either a control error correction is needed by using energy storage or a fast real-time peak power estimation method is needed to constantly scale the AGC set points based on the available plant power. Such a method was developed during this project and is described in detail in [15].

The ability of the BESS to follow the same AGC set point has been tested as well (Figure 12.). The BESS can provide this type of response with very high precision because it is not subject to resource variability like the PV plant.

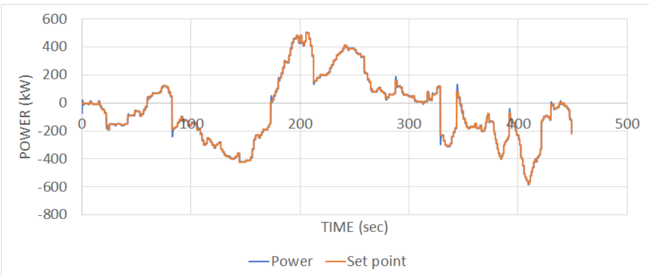

Figure 12. BESS following AGC set points

VII. Dispatchability of PV-BESS Plant

The combined PV-BESS output can be shaped based on various revenue optimization algorithms, changing electricity prices, dispatch signals from the system operator, and types of reliability services the PV-BESS plant is providing. The NREL PV-BESS system combines an AC-coupled PV array (rated at 430 kW) and a BESS (rated at 1 MW/1 MWh), which creates an opportunity to test algorithms for multihour PV energy shifting and scheduling in addition to output profile shaping with a large degree of flexibility. The plant controller developed at NREL can provide dispatchable operation without PV curtailment while operating within the energy capacity and power rating constraints of the PV-BESS plant.

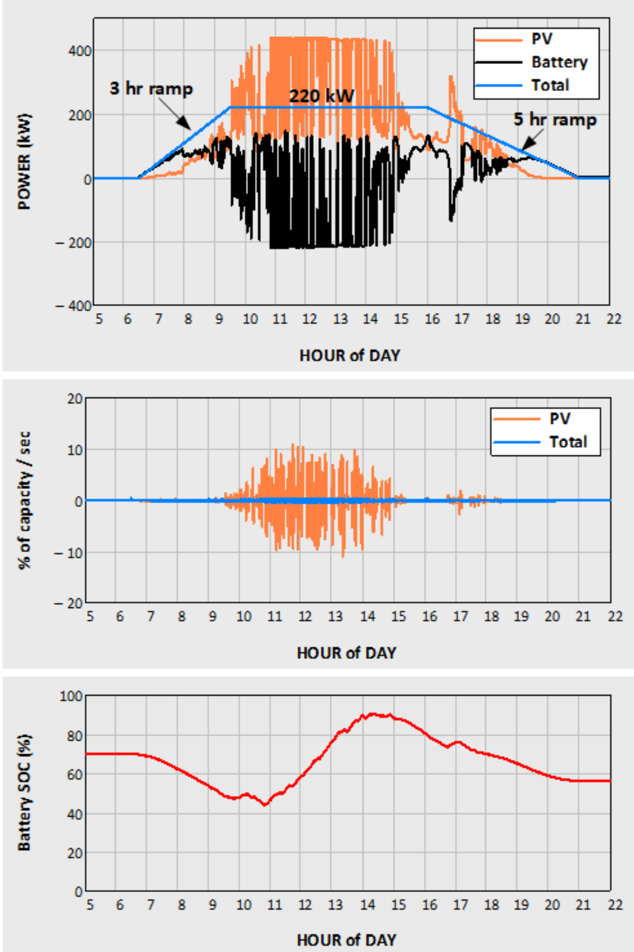

Figure 13. Example of production profile-shaping PV-BESS system

One example of output-shaping operation is shown in Figure 13 for a PV-BESS system with measured PV power output under highly variable solar resource conditions present at the Flatirons site. In this example, the BESS is controlled to provide 3-h morning and 5-h evening ramps as well as steady baseload-like operation during the middle of the day. The initial SOC of the BESS happened to be at 70%, and during the day, the BESS is mainly charging (from PV only) in the morning and discharging in the evening while balancing the PV variability during the whole day, with the end SOC near 60%.

In this case, the BESS—because of a larger power rating than the PV plant—has sufficient headroom to modulate its power above the dispatched level for other services, such as primary response and up-regulation. Other desired aggregate profiles of the PV-BESS plant can be achieved similar to the case shown in Figure 13.

VIII. Black Start of PV Plant with BESS

Several experiments were conducted using the BESS as a black-start resource for the PV plant. This experiment was conducted with the BESS inverter set into the soft black start so it was ramping the voltage from zero to the full level during a 200-ms time period to minimize the inrush current in the PV plant transformer, which is connected to the circuit during the whole process.

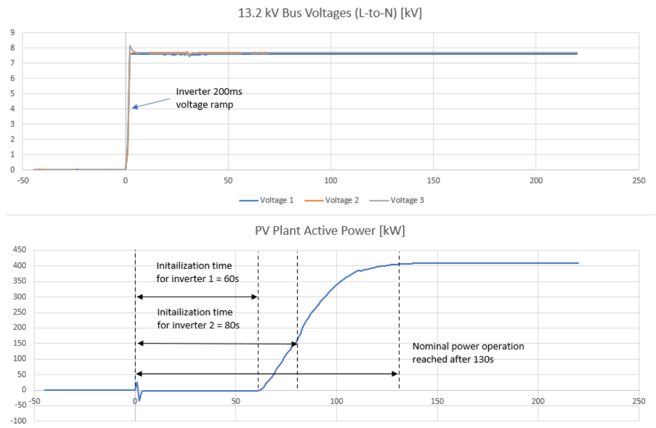

Figure 14. Soft black start of PV system using grid-forming BESS

Results of the soft black start for the 430-kW PV plant using the 1-MW/1-MWh BESS as a black-start resource are shown in Figure 14.

The SMA inverter of the BESS is increasing its voltage with a 200-ms ramp to minimize the inrush currents in the PV plant transformer, as shown in Figure 15. The peak BESS current during the start is only 5% of the inverter's rated current. After the transformer is energized, the initialization timers trigger in the inverters (60 s for 45-kW inverters and 80 s for 125-kW inverters).

The system restoration is a gradual process—based on priorities as defined in the restoration plans—until the totality of the customers are reenergized. The system restoration strategies depend on the type of systems being restored and the location of the black-start resource in the grid. PV-BESS plants with grid-forming capability can participate in various restoration schemes and will become a critical component of a future resilient grid.

IX. Power System Oscillations Damping Controls

Power system oscillations triggered by disturbances—such as generation outages or transmission line faults—can result in system separation because of large swings in the active power flow over intertie lines, potentially leading to major blackout events [17]–[20]. Multiple approaches have been proposed for damping inter-area oscillations. One method using energy storage systems installed in areas that can oscillate against one another and with real power injection at each location using a damping control system is described in [16].

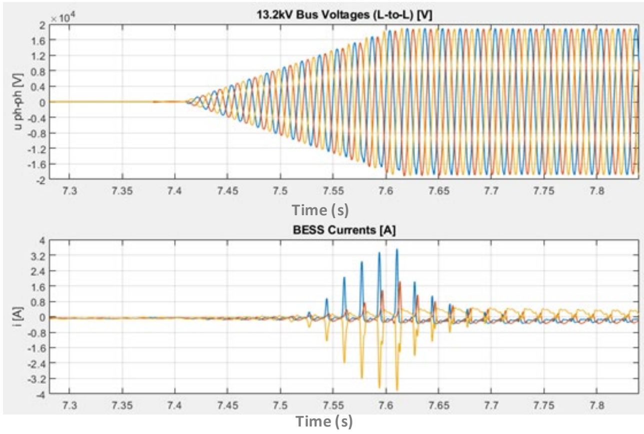

Figure 15. Soft black start of PV system using BESS (zoomed into inverter voltage ramping period)

To test the ability of the PV-BESS plant to modulate its active power output at different frequencies that are typical to inter-area and local modes (0.1–1.5 Hz), the plant output was slightly curtailed by generating an active power reference slightly less than the maximum available power. In addition to the slowly varying active power reference, sinusoidal modulation of different frequencies was added to the reference. A special control algorithm for testing such modulation characteristics for PV-BESS plants was developed and implemented in a real-time CGI controller during this project.

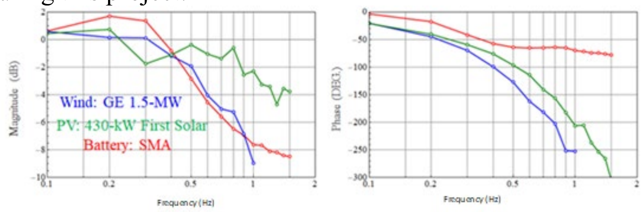

Figure 16. Gain and phase response plot for different resources

Figure 16 shows the transfer function gain from the active power reference to the active power output for 430-kW First Solar PV plant and the 1-MW/1-MWh BESS. For comparison, we also show the same for the GE 1.5-MW wind turbine. It is evident that all sources can provide active power modulation up to approximately 1 Hz. The PV plant exhibits maximum bandwidth for the active power modulations—inverter controls can be tuned further to improve the performance. The phase response in Figure 16 exhibits typical behavior of a delay—the phase response can be improved further by reducing the number and amount of delays from the active power reference to the active power output. Future work will implement power system stabilizer-like functionality in a PV plant and BESS, and the performance will be tested using PHIL experiments and later in the field.

Power system oscillation damping (POD) control for the PV-BESS plant was implemented and tested in the PHIL platform for a two-area power system, as shown in Figure 17.

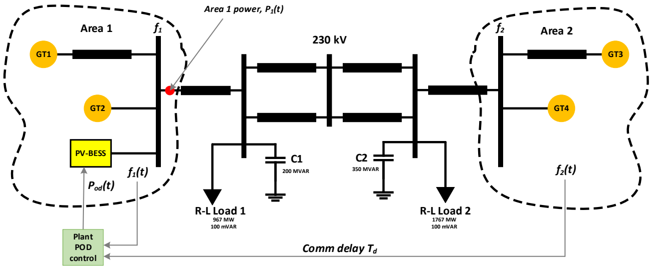

Figure 17. Two-area test system

Figure 18. Oscillations damped by POD control applied to PV-BESS plant

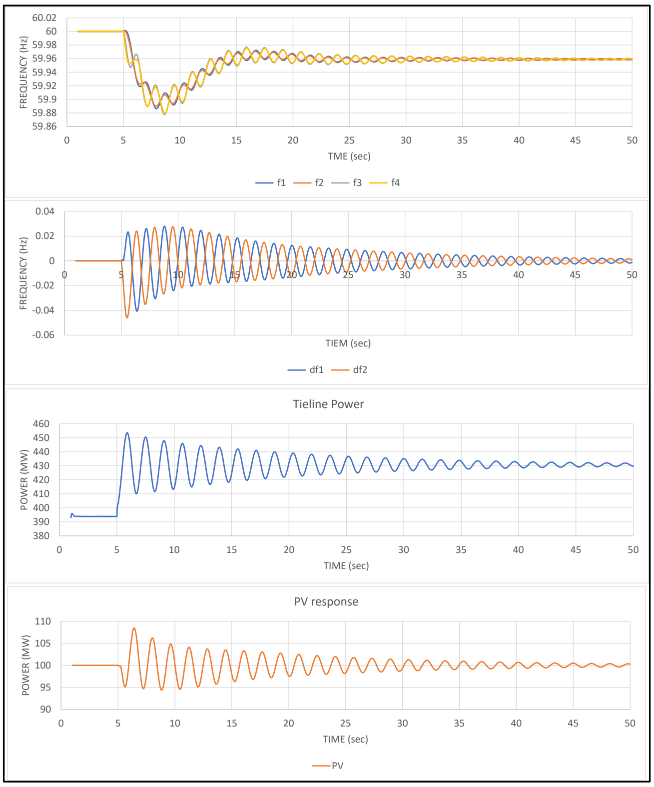

Figure 19. Oscillations damped by POD control applied to PV-BESS plant

The damping controller located in the PV-BESS plant located in Area 1 controls the power of the curtailed PV plant and BESS proportional to the frequency difference between areas 1 and 2 (the same control law as described in [16]). Generation in both areas is dominated with combined-cycle gas turbine generation. The damping behavior of the system shows good performance of the control law as applied to the PV plant controller in Area 1, as shown in Figure 19. Even with the 200-ms communications latency between areas 1 and 2 used in this case, the oscillations are effectively damped within approximately 20–25 s after the event starts. If a similar PV-BESS plant is in Area 2 with commanded power set points in accordance with the same control law, then the damping would be even more efficient.

X. Additional Tests

Because of the limited format of this paper, we describe here additional controls for PV-BESS plants that have been demonstrated during this project, including collective dynamic reactive and voltage control, various forms of variability smoothing, and revenue optimizations controls. These results will be presented in a separate paper.

XI. Conclusions

This paper presented results of the research project for developing controls and demonstrating how utility-scale solar PV-BESS plants can provide a wide range of essential reliability services to the grid using an "at scale" test bed consisting of a utility-scale PV array and BESS that can operate in grid-following or grid-forming modes under real and controlled grid conditions emulated by the CGI. The paper also showed how to black-start PV-BESS plants using grid-forming control of a battery storage inverter. Additional tests included demonstration of dispatchable operation of a PV-BESS plant and its ability to provide wide-area stability services in the form of power system inter-area oscillation damping. Future work will conduct demonstrations and evaluate the operation of PV-BESS systems in islanded grids.

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References

[1] "Renewabele increasingly beat Eeen cheapest coal competitors" IRENA press release, 02 June 2020.

[2] P. Denholm, R. Margolis, "Evaluating the limits of solar PV in traditional electric power system", Energy Policy 35 (2007) 2852-2861

[3] P. Denhom, K. Clark, M. O'Connel, "Challenges in integratong high levels of solar into the electrical generation and transmission system", NREL/TP-6A20-65800.

[4] B. Frew, W. Cole, P. Denholm, A, Will Fraser, N. Vincent, R.Margolis, "Sunny with a chance of curtailment: Operating the U.S> grid with very higj levbels of solar PV", iScence 21 publicartion, 436-447, November 2019

[5] V. Gevorgian, C. Loutan, M. Morjaria, et.al. "Demonstration of advanced ancillary service controls by a large utility-scale PV power plant in California". NREL draft report in review, December 2016

[6] P. Denholm, R. Margolis, "Energy storage requirements for achieving 50% solar PV penetration in California". NREL report, August 2016

[7] M. Morjaria, D. Anichkov, V. Chadliev, and S. Soni, "A Grid-Friendly Plant," IEEE Power and Energy Magazine, May/June 2014

[8] W. Cole, A. Will Frazer, "Cost projections for utility-scale battery storage: 2020 update", NREL technical report, June 2020

[9] P. Brown, F. O'Sullivan, "Shaping PV array output to align with chnaging wholesale elctricity price profiles", Applied Energym, vol. 256, 15 December 2019

[10] W. Gorman, A. Mills, M. Bolinger, R. Wiser, N. Singhal, E. Ela, E. O'Shaughnessy, "Motivations and options for deploying hybrid generator-plus-battery projects within bulk power system", The Electricity Journal, 33/2020

[11] M. Bortolini et al., "Technical and economic design of photovoltaic and battery energy storage system," Energy Conversion and Management, vol. 86, pp. 81 – 92, 2014.

[12] Y. Khawaja, D. Giaouris, H. Patskis, M. Dahidah, "Optimal Cost-Based Model for Sizing Grid-Connected PV and Battery Energy System", 2017 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT), October 11-13, 2017

[13] V. Gevorgian, B. O'Neill Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants. NREL report, 2016

[14] V. Gevorgian et. al. "WGRID-49 GMLC Project Report", NREL, August 2019, https://www.osti.gov/biblio/1558905

[15] V. Gevorgian, "Highly Accurate Method for Real-Time Active Power Reserve Estimation for Utility-Scale Photovoltaic Plants", NREL report, February 2019

[16] J. C. Neely, R. H. Byrne, R.T. Elliott, C. Silva-Monroy, D. Schoenwald, D. Trudnowski, M, Donnely, "Daming of Inter-area Oscillations using Energy Storage", IEEE PES GM meeting paper, July 2013

[17] "Innovative Ancillary Services", IRENA report, 2019

[18] M. Singh, A. J. Allen, E. Muljadi, V. Gevorgian, Y. Zhang, and S. Santoso, "Interare oscillation damping controls for wind power plants," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 967-975, July 2015.

[19] "Oscillation Event 03.12.207 – System Protection and Dynamics WG," ENTSO-E, Brussels, Belgium, 2018.

[20] F. R. Schleif and J. H. White, "Damping for the northwest – southwest oscillations—an analog study," *IEEE Trans. Power App. And Syst.*, vol. 85, no. 2, pp. 1239-1247, Dec. 1966.

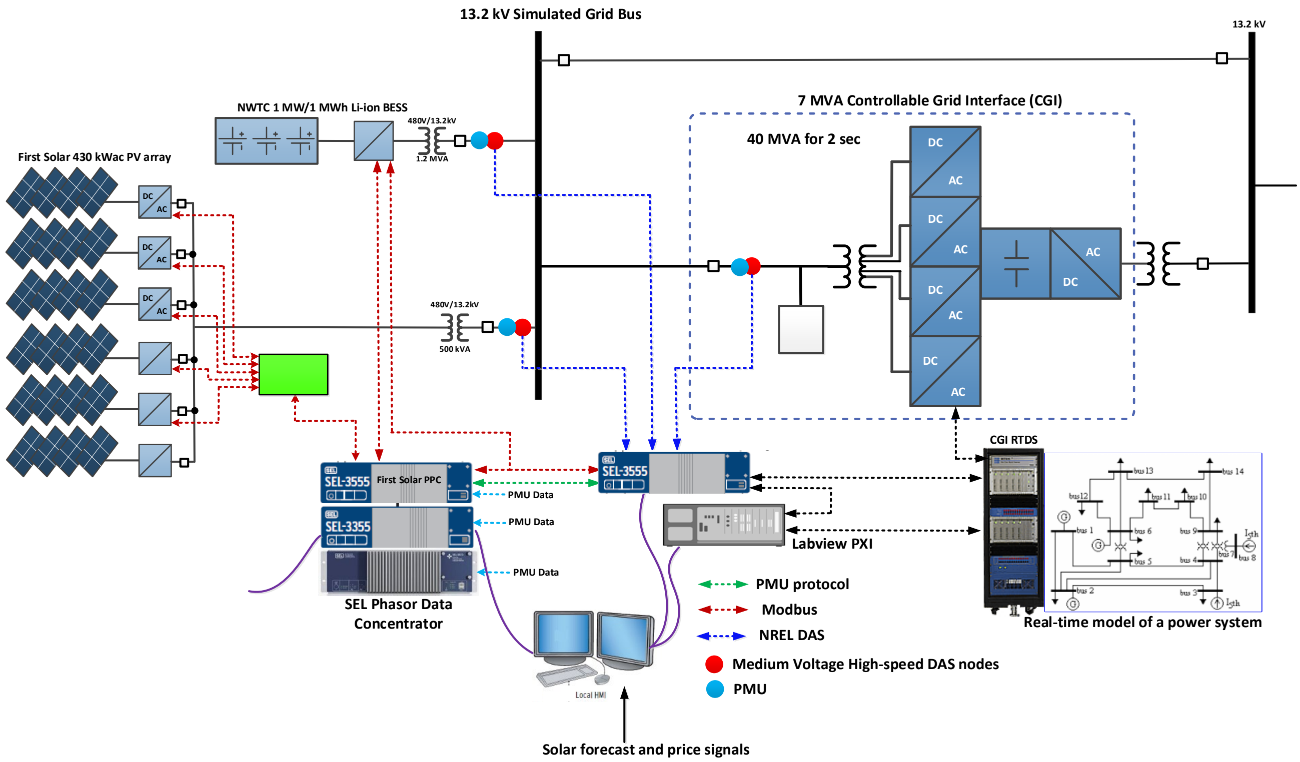

Figure 20. PV plant and BESS integrated with 7-MVA CGI

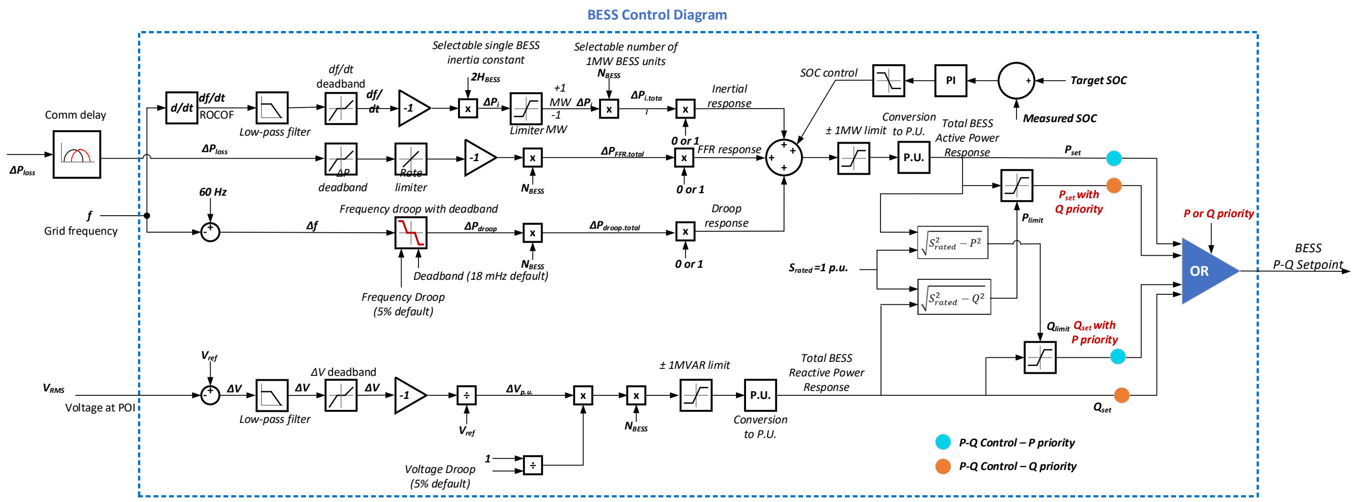

Figure 21. Controller diagram for active and reactive power control services by BESS